

PATENT APPLICATION

5

**MULTI-LAYER, SELF-ALIGNED VERTICAL COMBDRIVE ELECTROSTATIC
ACTUATORS AND FABRICATION METHODS**

INVENTORS

10 Behrang Behin and Satinderpall Pannu

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is based on Provisional application 60/192,097 filed 03/24/00, which is herein incorporated by reference.

FIELD OF THE INVENTION

This invention relates generally to micro-electromechanical systems (MEMS). More particularly, it relates to vertical comb-drive electrostatic actuators and fabrication methods.

BACKGROUND ART

Microstructures fabricated using silicon integrated processing techniques are used in a wide variety of sensing, actuating, and optical applications. One particularly useful device is a comb-drive actuator, which consists of two comb-like structures, one mobile and one stationary, whose fingers are interdigitated. When a potential difference is applied to the alternating fingers, a resulting electrostatic force causes the mobile fingers to move to maximize the overlap area. While the force provided by each finger is quite small, including a large number of fingers in the comb drive allows for application of relatively large forces using low voltages, particularly when there is a large capacitive overlap area.

between two adjacent fingers. Comb drives also provide a method for accurate position measurement by sensing of the capacitance of the fingers.

5 Comb drives are differentiated by the plane of motion of the stationary and mobile combs with respect to one another. Linear or lateral comb-drive actuators provide translational motion in a single plane as the two comb devices move from being relatively spaced apart to being fully interdigitated.

10 The two comb structures remain in the same plane during actuation, with the stationary comb being fixed to a substrate, and the mobile comb moving with respect to the substrate. Examples of lateral comb drives are disclosed in U.S. Patent Nos. 5,025,346, issued to Tang et al., and 5,998,906, issued to Jerman et al.

15 It is often desirable to create out-of-plane actuation of various microstructures, such as rotation of mirrors about an axis parallel to a substrate. These rotating mirrors can be used individually or in array form for applications such as adaptive optics, visual displays, or fiber-optic switching.

20 Vertical comb-drive actuators provide rotational motion or translational motion perpendicular to a substrate. A micromachined electrostatic vertical actuator is disclosed in U.S. Patent No. 5,969,848, issued to Lee et al. The device of Lee et al. contains a set of vertical comb drives, with each drive capable of deflecting one edge of a square mirror. By relying on an asymmetric distribution of electrical fields when a bias voltage is applied between stationary and movable

25 comb fingers, the device of Lee et al. allows a small vertical (i.e. out of the plane of the comb fingers) motion of each mirror edge, at most 1.5 μm .

Larger movements and more simplified fabrication techniques are provided by staggered vertical comb drives, in which the stationary and moving comb drives are positioned parallel to one another, but with the plane of the moving comb above the plane of the stationary comb. The stationary comb fingers are an integral part of the substrate, while the moving comb is fixed to the substrate only through flexures. Applying a voltage between the two comb layers causes the moving comb teeth to be attracted to the stationary teeth and move to increase the overlap area, thereby exerting a force on the moving comb. Conventional fabrication techniques for vertical comb drives using standard photolithography processes require multiple steps for patterning the comb fingers. First, one set of comb teeth is fabricated on a first wafer layer. A second wafer layer is then bonded on top of the first wafer layer, followed by patterning and etching of a second layer to form the second set of comb teeth. The two wafer layers must be aligned to a very high precision; typical applications require comb fingers of $2 \mu\text{m}$ wide with a $6 \mu\text{m}$ separation distance, so that adjacent overlapped fingers are separated by only $2 \mu\text{m}$. Fabrication of vertical comb drives using this technique is prone to alignment problems. The steppers used to align the individual die on a wafer typically have a lateral resolution of $\pm 0.25 \mu\text{m}$. This resolution places a lower limit on the gap between adjacent comb fingers of about $2 \mu\text{m}$. Because two adjacent fingers are at different potentials during operation, they cannot contact each other. At high actuation voltages, errors in alignment of the fingers can cause sideways motion and instability in the comb drive. As a result, conventional fabrication techniques typically have low production yields.

There is a need, therefore, for a vertical comb drive that can be fabricated in fewer steps than required by conventional

fabrication methods, and that provides accurate alignment between two layers of comb fingers without requiring complicated alignment procedures.

SUMMARY

The present invention provides a multi-layer vertical comb drive actuator in which first and second comb fingers are simultaneously fabricated from a single multi-layer substrate. Because the fingers are fabricated together, the tedious alignment of the first and second fingers, required for fabricating conventional vertical comb-drive actuators, is avoided. Alignment is a direct result of the mask used in fabrication; thus the device is referred to as self-aligned. Each finger has two vertical conductive layers separated by an insulating layer or an air gap, and movement is provided by attraction of opposite layers of the first and second comb fingers.

The present invention provides a multi-layer vertical comb drive actuator containing a first comb structure having a plurality of first comb fingers, and a second comb structure having a plurality of second comb fingers. The second comb fingers extend from a comb bridge connected to the substrate through one or more flexures allowing vertical movement or rotational movement about an axis, and are positioned to be interdigitated with the first comb fingers. A movable element is attached to the rotatable flexure and coupled to the second comb structure. In one embodiment, both the first comb fingers and the second comb fingers may include first and second conductive layers electrically isolated from each other by an insulating layer or air gap. The first conductive layers of the first comb fingers may be substantially aligned with the first conductive layers of the second comb fingers, and the second conductive layers of the first comb fingers may

be substantially aligned with the second conductive layers of the second comb fingers. In an alternate embodiment, the second comb fingers may have only a first conductive layer in vertical alignment with the first conductive layer of the first comb fingers. In a further alternative embodiment, the second comb fingers have first and second conductive layers electrically isolated from each other by an insulating layer or air gap, and the first comb fingers have only a first conductive layer in alignment with the first conductive layer of the second comb fingers. In all embodiments, applying a voltage between the first and second layers of both first and second fingers causes the second comb structure to deflect, thereby maximizing the overlap area between the opposite layers of the first and second comb fingers. This vertical motion can be used to cause rotation if the movable element is mounted with a rotational degree of freedom.

Preferably, the actuator also has a position sensor for measuring the position of the movable element, and such position telemetry is fed into a feedback mechanism coupled to the voltage source for controlling the position of the moveable element. Combdrive fingers can also perform a position sensing function in addition to driving the angular rotation of the movable element attached thereto, by reading the capacitance of the fingers, indicating a position of the movable element. This position sensor embodiment may include capacitive sensing between any combinations of the comb layers. Alternatively, other position sensors, such as gap closing electrodes, additional comb fingers, piezoresistive strain gauges, coils, magnets, piezoelectric sensors and optical sensors, can be used to track the position of the movable element by one skilled in the art.

The actuator may have a feedback mechanism coupled to the position sensor and the voltage source for controlling the position of the movable element. The various position sensors may be used in tandem to increase the position tracking accuracy of the sensor. Furthermore, A first sensor can be linked to a second position sensor to configure or tune the second sensor enabling better accuracy position tracking than otherwise provided by two unlinked sensors.

10

Actuators of the present invention may be one-dimensional or two-dimensional gimbaled actuators. In a two-dimensional actuator the rotatable flexure may be attached to a frame, which may be mechanically engaged with a second rotatable flexure attached to a substrate and disposed along a second axis. The frame may also be coupled with a fourth comb structure that may have a plurality of fourth comb fingers that may be substantially co-planar with a plurality of third comb fingers extending from a third comb structure. Either or both of the third and fourth comb fingers may include first and second conductive layers electrically isolated from each other by an insulating layer, an air gap or by any means as one skilled in the art would be capable of applying. Third comb fingers and fourth comb fingers may be substantially interdigitated in a second predetermined engagement. The second axis may be substantially orthogonal to the first axis in this embodiment. Two independent voltages may be applied to control rotation of the actuator in two orthogonal first and second axes.

25

Also provided is a method of fabricating the different embodiments of the multi-layer vertical comb-drive actuator of the present invention. The method contains the following steps: providing a multi-layer structure having first and

15
20
25
30
35
40
45
50
55
60
65
70
75
80
85

5 second conductive layers separated by an insulating layer, and etching a top pattern in the first and second conductive layers and insulating layer to define the second and first comb fingers. The substrate may also have additional layers that are etched to define the bottom surfaces of the fingers.

10 In an alternate embodiment of the fabricating method, the first conductive layer may be removed from either the second or the first fingers in an additional step, to leave only the second conductive layer.

BRIEF DESCRIPTION OF THE FIGURES

15 Figs. 1A-1C are simplified schematic diagrams of multi-layer comb-drive actuators according to a first embodiment of the present invention.

20 Fig. 1D is a simplified plan view of a two-dimensional rotating actuator according to an alternative embodiment of the present invention.

25 Figs. 2A-2E are simplified cross-sectional views showing fabrication of a multi-layer comb-drive actuator according to a second embodiment of the present invention.

30 Figs. 3A-3I are simplified cross-sectional views showing fabrication of a multi-layer comb-drive actuator according to a third embodiment of the present invention.

DETAILED DESCRIPTION

Although the following detailed description contains many specifics for the purposes of illustration, anyone of ordinary skill in the art will appreciate that many variations and alterations to the following details are within the scope of the invention. Accordingly, the following embodiments of the invention are set forth without any loss of generality to, and without imposing limitations upon, the claimed invention.

The present invention provides a multi-layer vertical comb-drive actuator. Rather than being in different planes, the second comb fingers and first comb fingers lie in the same plane, each having first and second conductive layers separated by an insulating material, layer or air gap. The opposite layers of the second and first structures may be attracted to each other when voltage is applied between opposite layers of the first and second comb fingers, thus providing vertical and/or rotational motion.

10

A preferred embodiment of a multi-layer vertical comb-drive actuator 10 of the present invention is shown in Fig. 1A. The actuator 10 is formed on a substrate 12. A first comb structure 25, may be attached to the substrate 12 contain first comb fingers 14 that may have first conductive layers 16 and second conductive layers 18, which may be electrically isolated from each other by a first insulating layer 20. A second comb structure 22 may contain second comb fingers 24 that may extend from a comb bridge 26. The first comb fingers 14 may interdigitate with the second comb fingers 24. By way of example, the width of comb fingers 14 and 24 may be approximately 6 μm , with a separation distance between adjacent fingers of approximately 2 μm . The first comb structure 25 may be electrically isolated from the second comb structure 22 and/or the substrate 12.

25

In the embodiment shown in Fig 1A, the second comb fingers 24 and comb bridge 26 may have first conductive layers 30 and second conductive layers 28 electrically isolated from each other by an insulating layer 32. The insulating layers 20, 32 of the first and second comb fingers 14, 24 may include layers of insulating materials, such as silicon oxide or an insulating air gap. The first and second conductive layers 28, 30 of the second comb fingers 24 may be substantially

aligned with the corresponding first and second conductive layers 16, 18 of the first comb fingers 14.

A movable element 36 is mechanically coupled to the second comb structure 22 and the substrate 12 by a flexure 34. The flexure 34 may be a rotatable flexure that allows the movable element 36 to rotate about an axis 38. Such a rotatable flexure may be any structure suitable for providing a torque that counters rotation of the movable element 36 about the axis 38, such as one or more torsion hinges, cantilever flexures, serpentine flexures, or pin-and-staple hinges combined with one or more springs. The flexure 34 may also be a flexible member that allows vertical movement of the movable element with respect to the plane of the substrate 12. Alternatively, the torque that counters the movement of the moveable element 36 can be provided non-mechanically in a controlled, fixed and variable mode by application of e.g. magnetic or electrical forces onto the moveable element, or by controllably coupling the torque through piezoelectric strain gauge. Non-mechanical torque is useful to provide torsion force, for example, when using a pin and staple hinge flexure that otherwise would not provide a restoring force directed to the movable element

Operation of actuator 10 may be configured to share similarity to the operation of a conventional vertical comb-drive actuator. In one mode of operation, a voltage source 15 may apply a voltage between the first conductive layers 16, 30 and the second conductive layers 18, 28 respectively of the first and second comb finger 14, 24. In the embodiment depicted in Fig. 1A, the first conductive layers 16, 30 of the first and second comb fingers 14, 24 may be grounded and the voltage source 15 applies a voltage to the second conductive layers 18, 28 of the first and second comb fingers 14, 24. As a

result of the applied potential difference, the first conductive layers 30 of the second comb fingers 24 are attracted to the second conductive layers 18 of the first comb finger 14. The attraction causes the second comb structure 22 to move relative to the first comb structure 25, which, in turn, causes the movable element 36 to rotate about the axis 38.

Although Fig. 1A depicts a voltage applied to the second conductive layers 18, 28, while the first conductive layers 16, 30 are grounded, the invention is in no way limited to this particular configuration for applying a voltage between the first and second layers. The second conductive layers 18, 28 may be grounded while the voltage source 15 applies voltage to the first conductive layers 16, 30. Alternatively, the voltage source 15 may apply voltages of opposite polarity to the first and second conductive layers of the first and second comb fingers 14, 24. Voltage applied between the first and second comb fingers can be passed through various wave shaping schemes to optimize control of the movable element. Other methods of applying voltage between the first and second comb fingers are well known to those of average skill in the art.

A typical method of actuating the actuator 10 of Fig. 1A is to apply a voltage between the second conductive layers 18 and 28 of the second 24 and first 14 comb fingers and the first conductive layers 30 and 16 of the second 24 and first 14 comb fingers. In this configuration, the second comb finger 24 is in a state of unstable equilibrium in its nominal state, and can rotate either upwards or downwards, since for any given voltage, there are two stable states. In one of the stable states, the first conductive portion 30 of the second comb fingers 24 may be engaged with the second conductive portion

18 of the first comb fingers 14, while in the other of the two stable states, the second conductive portion 28 of the second comb fingers 24 is engaged with the first conductive portion 16 of the static comb fingers 14.

5

To alleviate this ambiguity, a more complex actuation scheme can be employed. Such a scheme requires the use of more than two voltages on the four conductive portions of the comb fingers. For example, the first conductive layers 16 and 30 of both the first 14 and second 24 comb finger can be kept at ground, while the second conductive layer 18 of the first comb 14 can be kept at V , and the second conductive layer 28 of the second comb 24 at $V + dV$, where dV is some additional voltage. This causes the second comb structure 22 to move down relative to the static comb structure 25. The actuation scheme can be quickly turned back to the original dual-voltage scheme once a preferred direction is established. Also, this scheme can be reversed to move the second comb fingers upward. Similar actuation schemes employing different voltages may also be employed to give the actuator a preferred direction of motion.

10

A major advantage of the multi-level vertical comb drive of the present invention is the ability to have push-pull actuation. Voltage differences on neighboring electrodes can only generate attractive forces. In conventional comb-drive actuators, a comb drive is used to pull an actuator in one direction, and a mechanical spring force or an opposing comb drive oriented opposite the first are used to pull it in the opposite direction. The present invention is unique in allowing a single set of comb fingers to pull the second structure in opposite directions, or in other words, to both pull and push the second structure. Push-pull actuation allows for a greater freedom to alter key system parameters using feedback schemes. Push-pull schemes allow both the

damping ratio and natural frequency of the system to be varied, while pull schemes only allow for the damping ratio to be varied. In the prior art vertical comb drives, only pull actuation methods are available. The pull actuation method of actuator 10 of Fig. 1A is described above. An example of push-pull actuation follows. The actuator can be brought to a certain position by application of a voltage to the second conductive portions 18 and 28 of both the first 14 and second 24 comb fingers, while keeping the first conductive layers 16 and 30 at ground. To push the actuator back to its rest position with a larger force than provided by the flexures, the polarity of the voltages on the two layers of either the first comb fingers 14 or the second comb fingers 24 can be reversed. The dynamics of the movable element can be altered by the application of simultaneous push-pull forces.

The actuator 10 may also be provided with a position sensor sense element for measuring a capacitance between the first and second comb fingers. For example, as shown in Fig. 1A, a sense element 17 may be coupled to a feedback element 19 that is coupled to the voltage source 15. The position sensor sense element 17 and feedback element 19 may be implemented in hardware, software or some combination of both such as an application specific integrated circuit (ASIC). Many sensing and feedback schemes are possible. For example, the sense element 17 may measure an amount of charge transferred to or from the comb fingers in response to the voltage applied by the voltage source 15. Alternatively, the position sense element 17 may apply a high frequency dither to either first or second comb fingers. The position sensor sense element 17 may then sense a return signal at the comb fingers not driven. A phase difference between the dither signal and return signal determines the capacitance. Such capacitance can be correlated with the relative positions of the second and first comb drives to obtain a very precise position measurement.

The position measurement may then be fed back to the voltage source 15 via the feedback element 19 to control the relative position of the movable element 36.

5 A differential capacitance measurement method may also be employed. This allows for greater sensitivity and intolerance to environmental variations such as temperature. In a differential capacitance sensing scheme, multiple capacitances are sensed, and the position may be calculated by using these 10 multiple capacitive measurements. For example, sense element 17 of Fig. 1A could sense the capacitance between the first conductive layer 30 of the second comb fingers 24 and the first conductive layer 16 of the first comb fingers 14, and comparing it with the capacitance between the first conductive layer 30 of the second comb fingers 14 and the second conductive layer 18 of the first comb fingers 14. Alternatively, a single capacitance may be sensed between any two electrically isolated layers, e.g., layers 30 and 16, layers 18 and 28, layers 16 and 28, or layers 18 and 30. Similar methods may be employed with the structures in Figs. 1B and 1C.

25 The present invention accommodates alternative position sensors comprised of gap closing electrodes, additional comb fingers, piezoresistive strain gauges, coils, magnets, piezoelectric sensors, optical sensors and combinations thereof.

30 Fig. 1B shows an alternate embodiment of a multi-layer comb-drive actuator 40 of the present invention. Actuator 40 may share similarity to actuator 10. The actuator 40 may generally include a first comb structure 25' mechanically coupled to a substrate 12' and a second comb structure 41

5 attached to a movable element 36'. The movable element 36' may be mechanically coupled to the substrate by one or more flexures 34', e.g., for rotation about an axis 38'. The second comb structure 41 may include second comb fingers 42 that extend from a comb bridge 46. One or more second comb fingers 42 of the second comb structure 41 have only a first conductive layer 44, and do not have second conductive layers or insulating layers.

10 10 The first comb structure 25' may have first comb fingers 14' that interdigitate with the second comb fingers 42. The first comb fingers may include first and second conductive layers 16', 18' electrically isolated by an insulating layer 20' or by an air gap. The first conductive layer 16' of the first comb fingers 14' may be substantially aligned with the first conductive layer 44 of the second comb fingers. Alternatively, the second conductive layer 18' of the first comb fingers 14' may be substantially aligned with the first conductive layer 44 of the second comb fingers.

20 20 Actuator 40 may be configured to operate similar to that of actuator 10. For example, a voltage source 15' may apply a voltage difference between the conductive layer 44 of the second comb fingers 42 and either of the conductive layers 16', 18' of the first comb fingers 14'. The voltage source 15' may also be coupled to a sense element 17' and feedback element 19' as described above.

30 30 Fig. 1C shows a further alternate embodiment of a multi-layer comb-drive actuator 50 that generally includes a first comb structure 51 mechanically coupled to a substrate 12'' and a second comb structure 22'' attached to a movable element 36''. The movable element 36'' may be mechanically coupled to the substrate by one or more flexures 34'', e.g., for rotation

about an axis 38". The second comb structure 22" may have second comb fingers 24" that extend from a comb bridge 26". The comb bridge 26" and second comb fingers 24" may have first and second conductive layers, 28", 30" electrically isolated by an insulating layer 32". The first comb structure 51 may be similar to the first comb structure 25 of Fig. 1A except that one or more first comb fingers 52 of the second comb structure 51 may have only first conductive layers 54, and may not have second conductive layers or insulating layers. The first conductive layer 54 of the first comb fingers 52 may be substantially aligned with the first conductive layer 30" of the second comb fingers 24". Alternatively, the first conductive layer 54 of the first comb fingers 52 may be substantially aligned with the second conductive layer 28" of the second comb fingers.

Actuator 50 can be configured to operate similar to that of actuator 10 and/or actuator 40. For example, a voltage source 15" may apply a voltage difference between the conductive layer 54 of the comb fingers 52 and either of the conductive layers 28", 30" of the second comb structure 22". The voltage source 15" may also be coupled to a sense element 17" and feedback element 19" as described above. The dynamics of the movable element can be altered by the application of simultaneous push-pull forces.

When actuators 10, 40, or 50 are used for positioning a movable element, such as a micromirror, the mirror may be formed integrally with the second comb structure. Rotation of the second comb structure may cause the mirror to tilt, and the rotational flexures 34, 34", 34" may provide a restoring torque. The actuation mechanism may be integrated with the mirror during manufacture, and may be linear and stable over quite a large range of motion. A relatively large torque

allows actuation at high speed, and enables large-angle steady-state beam positioning. Furthermore, the integrated device allows for capacitive position sensing. Thus the integrated device provides significant advantages over existing magnetic, piezoelectric, and gap-closing actuators. However, the existing stated actuators can be used in coordination with the present invention to modify the dynamic characteristics of the movable element as desired by the application.

10

The present invention further provide a two-dimensional rotating actuator including two multi-layer vertical comb-drives of the types depicted in Figs. 1A-C, which are arranged in a gimbaled structure and a rotating element mechanically coupled to both of the comb-drives as shown in Fig. 1D according to an alternative embodiment of the present invention. As shown in Fig. 1D, in a two-dimensional rotating actuator 100, a second comb structure 118 having a plurality of second comb fingers 117 that substantially interdigitate with a plurality of first comb fingers 115 extending from a first comb structure 116. Either or both of the first and second comb fingers 115 and 117 may include two conductive layers separated by an insulating layer or an air gap as described in Figs. 1A-C. First comb fingers 115 and second comb fingers 117 may be substantially interdigitated in a first predetermined engagement. Note that in the embodiment of Fig. 1D, first comb fingers 115 are electrically isolated from second comb fingers 117, the substrate 102, frame 104 and rotating element 106.

25

The rotating element 106 may include a reflecting surface so that the device 100 may operate as a MEMS mirror. The rotating element 106 may be attached to a first rotatable flexure 108 disposed along a first axis 124. Rotating element

30

106 may also be mechanically engaged with second comb structure 118 along with first movable comb fingers 117. First rotatable flexure 108 may be attached to a frame 104, which in turn may be mechanically engaged with a second rotatable flexure 110 attached to a substrate 102 and disposed along a second axis 126. Frame 104 may also be coupled with a fourth comb structure 114 having a plurality of fourth comb fingers 113 that substantially interdigitate with a plurality of third comb fingers 111 extending from a third comb structure 112. The second comb structure 112 may be electrically isolated from the substrate 102, the frame 104, the rotating element 106, and the fourth comb fingers 113. Either or both of the third and fourth comb fingers 111 and 113 may include two conductive layers separated by an insulating layer or an air gap as described in Figs. 1A-C. Third comb fingers 111 and fourth comb fingers 113 are substantially interdigitated in a second predetermined engagement. Third comb fingers 111 are likewise electrically isolated from fourth comb fingers 113. Moreover, first comb fingers 115 may be made to be electrically isolated from third comb fingers 111. As such, the first and second comb-drives are coupled by way of frame 104. First axis 124 is configured to be substantially orthogonal to second axis 126 in this embodiment.

25 It should be noted that first and second rotatable flexures 108, 110, frame 104, rotating element 106, together with the first and second comb-drives, may be substantially co-planar. Furthermore, the rotatable flexures 108, 110 may be any structure suitable for providing a torque that counters rotation of the second comb fingers about the first axis 124, such as one or more torsion hinges, cantilever flexures, serpentine flexures or pin-and-staple hinges combined with one or more springs. Non-mechanical torque can be dynamically

provided through other stated principals, including magnetic principles, and that the telemetry sensing of a first flexure may be linked to dynamically configure a second torque element to achieve higher accuracy torsion control than the two unlinked elements could otherwise provide.

5 Applying a voltage from a source 120 between the second comb fingers 117 and the first comb fingers 115 attracts the second comb fingers 117 to the first comb fingers 115, which causes the first comb structure 118 to move vertically relative to the second comb structure 116. Thus a torque is exerted on the rotating element 106, which causes the rotating element 106 to rotate about the first axis 124. Applying another 10 voltage from another source 122 between the fourth comb fingers 113 and the third comb fingers 111 attracts the fourth comb fingers 113 to the third comb fingers 111, which causes the fourth comb structure 114 to move vertically relative to the third comb structure 112. Thus, a torque is exerted on the frame 104, which causes the frame 104 to rotate about the second axis 126. Therefore the rotating element 106 can 15 rotate about the second axis 126. The applied voltages from the sources 120 and 122 are typically about 30V. The applied voltages from the sources 120 and 122 may be adjusted to 20 independently control the angle between the frame 104 and the substrate 102, and the angle between the rotating element 106 and the frame 104.

25 As described above, the capacitance of the vertical comb-drives generally can be measured to monitor the angular positions of the rotating element 106 and the frame 104. Furthermore, capacitance across the comb fingers 115 and 117, or 111 and 113 may be used to sense the angular position of the rotating element 106. For example capacitance sensors 132 and 134 may be coupled to the comb fingers 111 and 115.

respectively. The capacitance sensors 132, 134 may provide feed back to the voltage sources 120, 122 via controllers 136, 138. Capacitive position monitoring signals from the sensors 132, 134 may be used to implement closed-loop feedback control 5 the angles of the rotating element 106 and the frame 104 via the sensors 136, 138. Therefore, capacitive angle signals may be used in a servo loop to actively control the position of the rotating element 106. Several alternate position sensing 10 techniques, such as gap closing electrodes, additional comb fingers, piezoresistive strain gauges, coils, magnets, piezoelectric sensors, optical sensors and combinations thereof could be used instead of capacitive sensing from the comb fingers, and in tandem with the capacitive sensing feature of the present invention. Furthermore, a first position sensor element could be linked to configure a second position sensor element to achieve higher accuracy position sensing than otherwise provided by two unlinked sensors.

The present invention also provides significant advantages over existing vertical comb-drive actuators in its preferred fabrication method. Because the second comb fingers and first comb fingers are in the same vertical plane, they can be formed in a single step from a single multi-layer structure, providing for automatic alignment of the fingers. A method of 25 fabricating a multi-layer vertical comb-drive structure such as that depicted in Fig. 1A is illustrated in Figs. 2A-2E according to a second embodiment of the present invention. For a silicon-on-insulator (SOI) substrate, all of the steps can be performed using standard photolithography tools, an 30 oxide etcher, and a deep reactive-ion silicon etcher, all of which are available in commercial fabrication foundries. The following describes exemplary methods for fabricating comb-drive actuators of the present invention. It is to be understood that other fabrication methods may be used to make

such structures, and that structures made by other methods are within the scope of the present invention.

Fig. 2A shows a cross-sectional view of a multi-layer substrate 200 containing a first conductive layer 202, a second conductive layer 204, a first insulating layer 208, a optional second insulating layer 210, and an optional substrate layer 206. Conductive layers 202 and 204 and the substrate layer 206 may be made of any suitable material including , but not limited to silicon, silicon-germanium, silicon-carbide, nickel, and gold. Conductive layers 202 and 204 are preferably silicon. Insulating layers 208 and 210 may be made of any suitable insulating material including, but not limited to, silicon-nitride, silicon-oxide, silicon-carbide, quartz, high resistivity silicon, high resistivity silicon germanium, polyimide, or a polymeric film. Insulating layers 208 and 210 are preferably a silicon oxide formed by thermal oxidation of silicon conductive layers 202 and 204, which are then bonded together. The substrate layer 206 is preferably also silicon. Other substrates and combinations of materials may also be used in different fabrication processes.

In Fig. 2B, a masking layer 212 (for example, photoresist or aluminum) is deposited and patterned on top of layer 202 defining a plurality of first and second comb fingers 214, 216 respectively as shown in Fig. 2C. Note that the pattern is not uniform in a direction perpendicular to the page, but rather forms a comb structure similar to those shown in Figs. 1A-1C. Fig. 2C shows the comb fingers formed as a result of deep reactive-ion etching of first and second conductive layers 202 and 204 (e.g. silicon) and first insulating layer 208 (e.g. silicon oxide) of Fig. 2B, after removal of the remaining masking layer 212. In Fig. 2D, a portion of optional substrate layer 206 (e.g. silicon) is etched away to

release a bottom surface of the comb fingers 214, 216, leaving first comb fingers 214 and second comb fingers 216. Second insulating layer 210 is also etched away either by anisotropic etching from the bottom side or by isotropic etching. 5 Optional substrate layer 206 may instead be left intact, limiting motion of the second comb fingers 216 to only motion above the substrate. Note that second comb fingers 216 are connected to a second comb bridge in a plane parallel to the plane of the paper, either above or below the paper. The 10 first insulating layer 208 is optionally removed. Operation of the resulting actuator 220 is shown in Fig. 2E. A potential is applied to the top layers of both the second and first (or stationary) comb fingers, while the bottom layers of both types of comb fingers are grounded. The potential can cause the second combs fingers 216 to move as shown.

3015
3020
3025
3030
3035
3040
3045
3050
3055
3060
3065
3070
3075
3080
3085
3090
3095
3100
3105
3110
3115
3120
3125
3130
3135
3140
3145
3150
3155
3160
3165
3170
3175
3180
3185
3190
3195
3200
3205
3210
3215
3220
3225
3230
3235
3240
3245
3250
3255
3260
3265
3270
3275
3280
3285
3290
3295
3300
3305
3310
3315
3320
3325
3330
3335
3340
3345
3350
3355
3360
3365
3370
3375
3380
3385
3390
3395
3400
3405
3410
3415
3420
3425
3430
3435
3440
3445
3450
3455
3460
3465
3470
3475
3480
3485
3490
3495
3500
3505
3510
3515
3520
3525
3530
3535
3540
3545
3550
3555
3560
3565
3570
3575
3580
3585
3590
3595
3600
3605
3610
3615
3620
3625
3630
3635
3640
3645
3650
3655
3660
3665
3670
3675
3680
3685
3690
3695
3700
3705
3710
3715
3720
3725
3730
3735
3740
3745
3750
3755
3760
3765
3770
3775
3780
3785
3790
3795
3800
3805
3810
3815
3820
3825
3830
3835
3840
3845
3850
3855
3860
3865
3870
3875
3880
3885
3890
3895
3900
3905
3910
3915
3920
3925
3930
3935
3940
3945
3950
3955
3960
3965
3970
3975
3980
3985
3990
3995
4000
4005
4010
4015
4020
4025
4030
4035
4040
4045
4050
4055
4060
4065
4070
4075
4080
4085
4090
4095
4100
4105
4110
4115
4120
4125
4130
4135
4140
4145
4150
4155
4160
4165
4170
4175
4180
4185
4190
4195
4200
4205
4210
4215
4220
4225
4230
4235
4240
4245
4250
4255
4260
4265
4270
4275
4280
4285
4290
4295
4300
4305
4310
4315
4320
4325
4330
4335
4340
4345
4350
4355
4360
4365
4370
4375
4380
4385
4390
4395
4400
4405
4410
4415
4420
4425
4430
4435
4440
4445
4450
4455
4460
4465
4470
4475
4480
4485
4490
4495
4500
4505
4510
4515
4520
4525
4530
4535
4540
4545
4550
4555
4560
4565
4570
4575
4580
4585
4590
4595
4600
4605
4610
4615
4620
4625
4630
4635
4640
4645
4650
4655
4660
4665
4670
4675
4680
4685
4690
4695
4700
4705
4710
4715
4720
4725
4730
4735
4740
4745
4750
4755
4760
4765
4770
4775
4780
4785
4790
4795
4800
4805
4810
4815
4820
4825
4830
4835
4840
4845
4850
4855
4860
4865
4870
4875
4880
4885
4890
4895
4900
4905
4910
4915
4920
4925
4930
4935
4940
4945
4950
4955
4960
4965
4970
4975
4980
4985
4990
4995
5000
5005
5010
5015
5020
5025
5030
5035
5040
5045
5050
5055
5060
5065
5070
5075
5080
5085
5090
5095
5100
5105
5110
5115
5120
5125
5130
5135
5140
5145
5150
5155
5160
5165
5170
5175
5180
5185
5190
5195
5200
5205
5210
5215
5220
5225
5230
5235
5240
5245
5250
5255
5260
5265
5270
5275
5280
5285
5290
5295
5300
5305
5310
5315
5320
5325
5330
5335
5340
5345
5350
5355
5360
5365
5370
5375
5380
5385
5390
5395
5400
5405
5410
5415
5420
5425
5430
5435
5440
5445
5450
5455
5460
5465
5470
5475
5480
5485
5490
5495
5500
5505
5510
5515
5520
5525
5530
5535
5540
5545
5550
5555
5560
5565
5570
5575
5580
5585
5590
5595
5600
5605
5610
5615
5620
5625
5630
5635
5640
5645
5650
5655
5660
5665
5670
5675
5680
5685
5690
5695
5700
5705
5710
5715
5720
5725
5730
5735
5740
5745
5750
5755
5760
5765
5770
5775
5780
5785
5790
5795
5800
5805
5810
5815
5820
5825
5830
5835
5840
5845
5850
5855
5860
5865
5870
5875
5880
5885
5890
5895
5900
5905
5910
5915
5920
5925
5930
5935
5940
5945
5950
5955
5960
5965
5970
5975
5980
5985
5990
5995
6000
6005
6010
6015
6020
6025
6030
6035
6040
6045
6050
6055
6060
6065
6070
6075
6080
6085
6090
6095
6100
6105
6110
6115
6120
6125
6130
6135
6140
6145
6150
6155
6160
6165
6170
6175
6180
6185
6190
6195
6200
6205
6210
6215
6220
6225
6230
6235
6240
6245
6250
6255
6260
6265
6270
6275
6280
6285
6290
6295
6300
6305
6310
6315
6320
6325
6330
6335
6340
6345
6350
6355
6360
6365
6370
6375
6380
6385
6390
6395
6400
6405
6410
6415
6420
6425
6430
6435
6440
6445
6450
6455
6460
6465
6470
6475
6480
6485
6490
6495
6500
6505
6510
6515
6520
6525
6530
6535
6540
6545
6550
6555
6560
6565
6570
6575
6580
6585
6590
6595
6600
6605
6610
6615
6620
6625
6630
6635
6640
6645
6650
6655
6660
6665
6670
6675
6680
6685
6690
6695
6700
6705
6710
6715
6720
6725
6730
6735
6740
6745
6750
6755
6760
6765
6770
6775
6780
6785
6790
6795
6800
6805
6810
6815
6820
6825
6830
6835
6840
6845
6850
6855
6860
6865
6870
6875
6880
6885
6890
6895
6900
6905
6910
6915
6920
6925
6930
6935
6940
6945
6950
6955
6960
6965
6970
6975
6980
6985
6990
6995
7000
7005
7010
7015
7020
7025
7030
7035
7040
7045
7050
7055
7060
7065
7070
7075
7080
7085
7090
7095
7100
7105
7110
7115
7120
7125
7130
7135
7140
7145
7150
7155
7160
7165
7170
7175
7180
7185
7190
7195
7200
7205
7210
7215
7220
7225
7230
7235
7240
7245
7250
7255
7260
7265
7270
7275
7280
7285
7290
7295
7300
7305
7310
7315
7320
7325
7330
7335
7340
7345
7350
7355
7360
7365
7370
7375
7380
7385
7390
7395
7400
7405
7410
7415
7420
7425
7430
7435
7440
7445
7450
7455
7460
7465
7470
7475
7480
7485
7490
7495
7500
7505
7510
7515
7520
7525
7530
7535
7540
7545
7550
7555
7560
7565
7570
7575
7580
7585
7590
7595
7600
7605
7610
7615
7620
7625
7630
7635
7640
7645
7650
7655
7660
7665
7670
7675
7680
7685
7690
7695
7700
7705
7710
7715
7720
7725
7730
7735
7740
7745
7750
7755
7760
7765
7770
7775
7780
7785
7790
7795
7800
7805
7810
7815
7820
7825
7830
7835
7840
7845
7850
7855
7860
7865
7870
7875
7880
7885
7890
7895
7900
7905
7910
7915
7920
7925
7930
7935
7940
7945
7950
7955
7960
7965
7970
7975
7980
7985
7990
7995
8000
8005
8010
8015
8020
8025
8030
8035
8040
8045
8050
8055
8060
8065
8070
8075
8080
8085
8090
8095
8100
8105
8110
8115
8120
8125
8130
8135
8140
8145
8150
8155
8160
8165
8170
8175
8180
8185
8190
8195
8200
8205
8210
8215
8220
8225
8230
8235
8240
8245
8250
8255
8260
8265
8270
8275
8280
8285
8290
8295
8300
8305
8310
8315
8320
8325
8330
8335
8340
8345
8350
8355
8360
8365
8370
8375
8380
8385
8390
8395
8400
8405
8410
8415
8420
8425
8430
8435
8440
8445
8450
8455
8460
8465
8470
8475
8480
8485
8490
8495
8500
8505
8510
8515
8520
8525
8530
8535
8540
8545
8550
8555
8560
8565
8570
8575
8580
8585
8590
8595
8600
8605
8610
8615
8620
8625
8630
8635
8640
8645
8650
8655
8660
8665
8670
8675
8680
8685
8690
8695
8700
8705
8710
8715
8720
8725
8730
8735
8740
8745
8750
8755
8760
8765
8770
8775
8780
8785
8790
8795
8800
8805
8810
8815
8820
8825
8830
8835
8840
8845
8850
8855
8860
8865
8870
8875
8880
8885
8890
8895
8900
8905
8910
8915
8920
8925
8930
8935
8940
8945
8950
8955
8960
8965
8970
8975
8980
8985
8990
8995
9000
9005
9010
9015
9020
9025
9030
9035
9040
9045
9050
9055
9060
9065
9070
9075
9080
9085
9090
9095
9100
9105
9110
9115
9120
9125
9130
9135
9140
9145
9150
9155
9160
9165
9170
9175
9180
9185
9190
9195
9200
9205
9210
9215
9220
9225
9230
9235
9240
9245
9250
9255
9260
9265
9270
9275
9280
9285
9290
9295
9300
9305
9310
9315
9320
9325
9330
9335
9340
9345
9350
9355
9360
9365
9370
9375
9380
9385
9390
9395
9400
9405
9410
9415
9420
9425
9430
9435
9440
9445
9450
9455
9460
9465
9470
9475
9480
9485
9490
9495
9500
9505
9510
9515
9520
9525
9530
9535
9540
9545
9550
9555
9560
9565
9570
9575
9580
9585
9590
9595
9600
9605
9610
9615
9620
9625
9630
9635
9640
9645
9650
9655
9660
9665
9670
9675
9680
9685
9690
9695
9700
9705
9710
9715
9720
9725
9730
9735
9740
9745
9750
9755
9760
9765
9770
9775
9780
9785
9790
9795
9800
9805
9810
9815
9820
9825
9830
9835
9840
9845
9850
9855
9860
9865
9870
9875
9880
9885
9890
9895
9900
9905
9910
9915
9920
9925
9930
9935
9940
9945
9950
9955
9960
9965
9970
9975
9980
9985
9990
9995
10000
10005
10010
10015
10020
10025
10030
10035
10040
10045
10050
10055
10060
10065
10070
10075
10080
10085
10090
10095
10100
10105
10110
10115
10120
10125
10130
10135
10140
10145
10150
10155
10160
10165
10170
10175
10180
10185
10190
10195
10200
10205
10210
10215
10220
10225
10230
10235
10240
10245
10250
10255
10260
10265
10270
10275
10280
10285
10290
10295
10300
10305
10310
10315
10320
10325
10330
10335
10340
10345
10350
10355
10360
10365
10370
10375
10380
10385
10390
10395
10400
10405
10410
10415
10420
10425
10430
10435
10440
10445
10450
10455
10460
10465
10470
10475
10480
10485
10490
10495
10500
10505
10510
10515
10520
10525
10530
10535
10540
10545
10550
10555
10560
10565
10570
10575
10580
10585
10590
10595
10600
10605
10610
10615
10620
10625
10630
10635
10640
10645
10650
10655
10660
10665
10670
10675
10680
10685
10690
10695
10700
10705
10710
10715
10720
10725
10730
10735
10740
10745
10750
10755
10760
10765
10770
10775
10780
10785
10790
10795
10800
10805
10810
10815
10820
10825
10830
10835
10840
10845
10850
10855
10860
10865
10870
10875
10880
10885
10890
10895
10900
10905
10910
10915
10920
10925
10930
10935
10940
10945
10950
10955
10960
10965
10970
10975
10980
10985
10990
10995
11000
11005
11010
11015
11020
11025
11030
11035
11040
11045
11050
11055
11060
11065
11070
11075
11080
11085
11090
11095
11100
11105
11110
11115
11120
11125
11130
11135
11140
11145
11150
11155
11160
11165
11170
11175
11180
11185
11190
11195
11200
11205
11210
11215
11220
11225
11230
11235
11240
11245
11250
11255
11260
11265
11270
11275
11280
11285
11290
11295
11300
11305
11310
11315
11320
11325
11330
11335
11340
11345
11350
11355
11360
11365
11370
11375
11380
11385
11390
11395
11400
11405
11410
11415
11420
11425
11430
11435
11440
11445
11450
11455
11460
11465
11470
11475
11480
11485
11490
11495
11500
11505
11510
11515
11520
11525
11530
11535
11540
11545
11550
11555
11560
11565
11570
11575
11580
11585
11590
11595
11600
11605
11610
11615
11620
11625
11630
11635
11640
11645
11650
11655
11660
11665
11670
11675
11680
11685
11690
11695
11700
11705
11710
11715
11720
11725
11730
11735
11740
11745
11750
11755
11760
11765
11770
11775
11780
11785
11790
11795
11800
11805
11810
11815
11820
11825
11830
11835
11840
11845
11850
11855
11860
11865
11870
11875
11880
11885
11890
11895
11900
11905
11910
11915
11920
1

306 and 308, respectively. Also shown is optional substrate layer 310. Structure 300 may be identical to structure 200 of Fig. 2A. Conductive layers 302 and 304 are preferably silicon, while insulating layers 306 and 308 are preferably a silicon oxide formed from thermal oxidation of silicon wafer layers 302 and 304, which are then bonded together.

In Fig. 3B, a first masking layer 312 (e.g. silicon oxide, aluminum, photoresist) is deposited and patterned on top of first conductive layer 302. Some of the remaining portions of the masking layer cover areas that will eventually become the first comb fingers. Next, in Fig. 3C, a second masking layer 314 (e.g. photoresist) is deposited on top of first masking layer 312 and then removed according to a second pattern, defining the location of eventual comb fingers. Layers 312 and 314 contain different types of masking material, so that one can be selectively removed without affecting the other. In Fig. 3D, regions 316 of first masking layer 312 that are not covered by second masking layer 314 are removed. This ensures that the second mask 314 defines the comb structures. Therefore, the alignment between the first mask 312 and the second mask 314 does not affect the comb widths. Next, in Fig. 3E, first conductive layer 302, first insulating layer 316, and second conductive layer 304 are etched, e.g., using deep reactive-ion etching (DRIE) to create two sets of comb fingers 322, 324 that will respectively become second and first comb fingers. The second masking layer 314 is then removed to create the structure of Fig. 3F, which is etched using DRIE or other anisotropic silicon etching methods to remove the first conductive layer 302 from alternating comb fingers. The resulting structure is shown in Fig. 3G. The fingers are then undercut in Fig. 3H, followed by optional removal of portions of the first and second insulating layers 306 and 308 and remaining first masking layer 312 to reveal an

actuator 330 of Fig. 3I. Insulating oxide layers may be removed using a timed HF etch. In the embodiment shown, second comb fingers 322 are connected to a second comb bridge in a plane parallel to the plane of the paper, either above or 5 below the page. The second comb bridge may be connected to the substrate through a torsion hinge or flexure that allows movement of the second comb structure. One method to operate actuator 330 is to apply a voltage V to the second comb fingers 322 and a bottom layer 324B of the first comb fingers 324, while a top layer 324A of first comb fingers 324 is 10 grounded, causing an electric force that moves the second comb fingers 322.

20
215
220
225
230
235
240
245
250
255
260
265
270
275
280
285
290
295
300
305
310
315
320
325
330
335
340
345
350
355
360
365
370
375
380
385
390
395
400
405
410
415
420
425
430
435
440
445
450
455
460
465
470
475
480
485
490
495
500
505
510
515
520
525
530
535
540
545
550
555
560
565
570
575
580
585
590
595
600
605
610
615
620
625
630
635
640
645
650
655
660
665
670
675
680
685
690
695
700
705
710
715
720
725
730
735
740
745
750
755
760
765
770
775
780
785
790
795
800
805
810
815
820
825
830
835
840
845
850
855
860
865
870
875
880
885
890
895
900
905
910
915
920
925
930
935
940
945
950
955
960
965
970
975
980
985
990
995
1000
1005
1010
1015
1020
1025
1030
1035
1040
1045
1050
1055
1060
1065
1070
1075
1080
1085
1090
1095
1100
1105
1110
1115
1120
1125
1130
1135
1140
1145
1150
1155
1160
1165
1170
1175
1180
1185
1190
1195
1200
1205
1210
1215
1220
1225
1230
1235
1240
1245
1250
1255
1260
1265
1270
1275
1280
1285
1290
1295
1300
1305
1310
1315
1320
1325
1330
1335
1340
1345
1350
1355
1360
1365
1370
1375
1380
1385
1390
1395
1400
1405
1410
1415
1420
1425
1430
1435
1440
1445
1450
1455
1460
1465
1470
1475
1480
1485
1490
1495
1500
1505
1510
1515
1520
1525
1530
1535
1540
1545
1550
1555
1560
1565
1570
1575
1580
1585
1590
1595
1600
1605
1610
1615
1620
1625
1630
1635
1640
1645
1650
1655
1660
1665
1670
1675
1680
1685
1690
1695
1700
1705
1710
1715
1720
1725
1730
1735
1740
1745
1750
1755
1760
1765
1770
1775
1780
1785
1790
1795
1800
1805
1810
1815
1820
1825
1830
1835
1840
1845
1850
1855
1860
1865
1870
1875
1880
1885
1890
1895
1900
1905
1910
1915
1920
1925
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
2075
2080
2085
2090
2095
2100
2105
2110
2115
2120
2125
2130
2135
2140
2145
2150
2155
2160
2165
2170
2175
2180
2185
2190
2195
2200
2205
2210
2215
2220
2225
2230
2235
2240
2245
2250
2255
2260
2265
2270
2275
2280
2285
2290
2295
2300
2305
2310
2315
2320
2325
2330
2335
2340
2345
2350
2355
2360
2365
2370
2375
2380
2385
2390
2395
2400
2405
2410
2415
2420
2425
2430
2435
2440
2445
2450
2455
2460
2465
2470
2475
2480
2485
2490
2495
2500
2505
2510
2515
2520
2525
2530
2535
2540
2545
2550
2555
2560
2565
2570
2575
2580
2585
2590
2595
2600
2605
2610
2615
2620
2625
2630
2635
2640
2645
2650
2655
2660
2665
2670
2675
2680
2685
2690
2695
2700
2705
2710
2715
2720
2725
2730
2735
2740
2745
2750
2755
2760
2765
2770
2775
2780
2785
2790
2795
2800
2805
2810
2815
2820
2825
2830
2835
2840
2845
2850
2855
2860
2865
2870
2875
2880
2885
2890
2895
2900
2905
2910
2915
2920
2925
2930
2935
2940
2945
2950
2955
2960
2965
2970
2975
2980
2985
2990
2995
3000
3005
3010
3015
3020
3025
3030
3035
3040
3045
3050
3055
3060
3065
3070
3075
3080
3085
3090
3095
3100
3105
3110
3115
3120
3125
3130
3135
3140
3145
3150
3155
3160
3165
3170
3175
3180
3185
3190
3195
3200
3205
3210
3215
3220
3225
3230
3235
3240
3245
3250
3255
3260
3265
3270
3275
3280
3285
3290
3295
3300
3305
3310
3315
3320
3325
3330
3335
3340
3345
3350
3355
3360
3365
3370
3375
3380
3385
3390
3395
3400
3405
3410
3415
3420
3425
3430
3435
3440
3445
3450
3455
3460
3465
3470
3475
3480
3485
3490
3495
3500
3505
3510
3515
3520
3525
3530
3535
3540
3545
3550
3555
3560
3565
3570
3575
3580
3585
3590
3595
3600
3605
3610
3615
3620
3625
3630
3635
3640
3645
3650
3655
3660
3665
3670
3675
3680
3685
3690
3695
3700
3705
3710
3715
3720
3725
3730
3735
3740
3745
3750
3755
3760
3765
3770
3775
3780
3785
3790
3795
3800
3805
3810
3815
3820
3825
3830
3835
3840
3845
3850
3855
3860
3865
3870
3875
3880
3885
3890
3895
3900
3905
3910
3915
3920
3925
3930
3935
3940
3945
3950
3955
3960
3965
3970
3975
3980
3985
3990
3995
4000
4005
4010
4015
4020
4025
4030
4035
4040
4045
4050
4055
4060
4065
4070
4075
4080
4085
4090
4095
4100
4105
4110
4115
4120
4125
4130
4135
4140
4145
4150
4155
4160
4165
4170
4175
4180
4185
4190
4195
4200
4205
4210
4215
4220
4225
4230
4235
4240
4245
4250
4255
4260
4265
4270
4275
4280
4285
4290
4295
4300
4305
4310
4315
4320
4325
4330
4335
4340
4345
4350
4355
4360
4365
4370
4375
4380
4385
4390
4395
4400
4405
4410
4415
4420
4425
4430
4435
4440
4445
4450
4455
4460
4465
4470
4475
4480
4485
4490
4495
4500
4505
4510
4515
4520
4525
4530
4535
4540
4545
4550
4555
4560
4565
4570
4575
4580
4585
4590
4595
4600
4605
4610
4615
4620
4625
4630
4635
4640
4645
4650
4655
4660
4665
4670
4675
4680
4685
4690
4695
4700
4705
4710
4715
4720
4725
4730
4735
4740
4745
4750
4755
4760
4765
4770
4775
4780
4785
4790
4795
4800
4805
4810
4815
4820
4825
4830
4835
4840
4845
4850
4855
4860
4865
4870
4875
4880
4885
4890
4895
4900
4905
4910
4915
4920
4925
4930
4935
4940
4945
4950
4955
4960
4965
4970
4975
4980
4985
4990
4995
5000
5005
5010
5015
5020
5025
5030
5035
5040
5045
5050
5055
5060
5065
5070
5075
5080
5085
5090
5095
5100
5105
5110
5115
5120
5125
5130
5135
5140
5145
5150
5155
5160
5165
5170
5175
5180
5185
5190
5195
5200
5205
5210
5215
5220
5225
5230
5235
5240
5245
5250
5255
5260
5265
5270
5275
5280
5285
5290
5295
5300
5305
5310
5315
5320
5325
5330
5335
5340
5345
5350
5355
5360
5365
5370
5375
5380
5385
5390
5395
5400
5405
5410
5415
5420
5425
5430
5435
5440
5445
5450
5455
5460
5465
5470
5475
5480
5485
5490
5495
5500
5505
5510
5515
5520
5525
5530
5535
5540
5545
5550
5555
5560
5565
5570
5575
5580
5585
5590
5595
5600
5605
5610
5615
5620
5625
5630
5635
5640
5645
5650
5655
5660
5665
5670
5675
5680
5685
5690
5695
5700
5705
5710
5715
5720
5725
5730
5735
5740
5745
5750
5755
5760
5765
5770
5775
5780
5785
5790
5795
5800
5805
5810
5815
5820
5825
5830
5835
5840
5845
5850
5855
5860
5865
5870
5875
5880
5885
5890
5895
5900
5905
5910
5915
5920
5925
5930
5935
5940
5945
5950
5955
5960
5965
5970
5975
5980
5985
5990
5995
6000
6005
6010
6015
6020
6025
6030
6035
6040
6045
6050
6055
6060
6065
6070
6075
6080
6085
6090
6095
6100
6105
6110
6115
6120
6125
6130
6135
6140
6145
6150
6155
6160
6165
6170
6175
6180
6185
6190
6195
6200
6205
6210
6215
6220
6225
6230
6235
6240
6245
6250
6255
6260
6265
6270
6275
6280
6285
6290
6295
6300
6305
6310
6315
6320
6325
6330
6335
6340
6345
6350
6355
6360
6365
6370
6375
6380
6385
6390
6395
6400
6405
6410
6415
6420
6425
6430
6435
6440
6445
6450
6455
6460
6465
6470
6475
6480
6485
6490
6495
6500
6505
6510
6515
6520
6525
6530
6535
6540
6545
6550
6555
6560
6565
6570
6575
6580
6585
6590
6595
6600
6605
6610
6615
6620
6625
6630
6635
6640
6645
6650
6655
6660
6665
6670
6675
6680
6685
6690
6695
6700
6705
6710
6715
6720
6725
6730
6735
6740
6745
6750
6755
6760
6765
6770
6775
6780
6785
6790
6795
6800
6805
6810
6815
6820
6825
6830
6835
6840
6845
6850
6855
6860
6865
6870
6875
6880
6885
6890
6895
6900
6905
6910
6915
6920
6925
6930
6935
6940
6945
6950
6955
6960
6965
6970
6975
6980
6985
6990
6995
7000
7005
7010
7015
7020
7025
7030
7035
7040
7045
7050
7055
7060
7065
7070
7075
7080
7085
7090
7095
7100
7105
7110
7115
7120
7125
7130
7135
7140
7145
7150
7155
7160
7165
7170
7175
7180
7185
7190
7195
7200
7205
7210
7215
7220
7225
7230
7235
7240
7245
7250
7255
7260
7265
7270
7275
7280
7285
7290
7295
7300
7305
7310
7315
7320
7325
7330
7335
7340
7345
7350
7355
7360
7365
7370
7375
7380
7385
7390
7395
7400
7405
7410
7415
7420
7425
7430
7435
7440
7445
7450
7455
7460
7465
7470
7475
7480
7485
7490
7495
7500
7505
7510
7515
7520
7525
7530
7535
7540
7545
7550
7555
7560
7565
7570
7575
7580
7585
7590
7595
7600
7605
7610
7615
7620
7625
7630
7635
7640
7645
7650
7655
7660
7665
7670
7675
7680
7685
7690
7695
7700
7705
7710
7715
7720
7725
7730
7735
7740
7745
7750
7755
7760
7765
7770
7775
7780
7785
7790
7795
7800
7805
7810
7815
7820
7825
7830
7835
7840
7845
7850
7855
7860
7865
7870
7875
7880
7885
7890
7895
7900
7905
7910
7915
7920
7925
7930
7935
7940
7945
7950
7955
7960
7965
7970
7975
7980
7985
7990
7995
8000
8005
8010
8015
8020
8025
8030
8035
8040
8045
8050
8055
8060
8065
8070
8075
8080
8085
8090
8095
8100
8105
8110
8115
8120
8125
8130
8135
8140
8145
8150
8155
8160
8165
8170
8175
8180
8185
8190
8195
8200
8205
8210
8215
8220
8225
8230
8235
8240
8245
8250
8255
8260
8265
8270
8275
8280
8285
8290
8295
8300
8305
8310
8315
8320
8325
8330
8335
8340
8345
8350
8355
8360
8365
8370
8375
8380
8385
8390
8395
8400
8405
8410
8415
8420
8425
8430
8435
8440
8445
8450
8455
8460
8465
8470
8475
8480
8485
8490
8495
8500
8505
8510
8515
8520
8525
8530
8535
8540
8545
8550
8555
8560
8565
8570
8575
8580
8585
8590
8595
8600
8605
8610
8615
8620
8625
8630
8635
8640
8645
8650
8655
8660
8665
8670
8675
8680
8685
8690
8695
8700
8705
8710
8715
8720
8725
8730
8735
8740
8745
8750
8755
8760
8765
8770
8775
8780
8785
8790
8795
8800
8805
8810
8815
8820
8825
8830
8835
8840
8845
8850
8855
8860
8865
8870
8875
8880
8885
8890
8895
8900
8905
8910
8915
8920
8925
8930
8935
8940
8945
8950
8955
8960
8965
8970
8975
8980
8985
8990
8995
9000
9005
9010
9015
9020
9025
9030
9035
9040
9045
9050
9055
9060
9065
9070
9075
9080
9085
9090
9095
9100
9105
9110
9115
9120
9125
9130
9135
9140
9145
9150
9155
9160
9165
9170
9175
9180
9185
9190
9195
9200
9205
9210
9215
9220
9225
9230
9235
9240
9245
9250
9255
9260
9265
9270
9275
9280
9285
9290
9295
9300
9305
9310
9315
9320
9325
9330
9335
9340
9345
9350
9355
9360
9365
9370
9375
9380
9385
9390
9395
9400
9405
9410
9415
9420
9425
9430
9435
9440
9445
9450
9455
9460
9465
9470
9475
9480
9485
9490
9495
9500
9505
9510
9515
9520
9525
9530
9535
9540
9545
9550
9555
9560
9565
9570
9575
9580
9585
9590
9595
9600
960

ONX-107A

It will be clear to one skilled in the art that the above embodiment may be altered in many ways without departing from the scope of the invention. Accordingly, the scope of the invention should be determined by the following claims and
5 their legal equivalents.